4. THERMOHALINE CIRCULATION

This lecture concerns the *thermohaline circulation* — the circulation resulting from changes to the temperature or salinity in some part of the ocean.

The lecture is organised around the following topics:

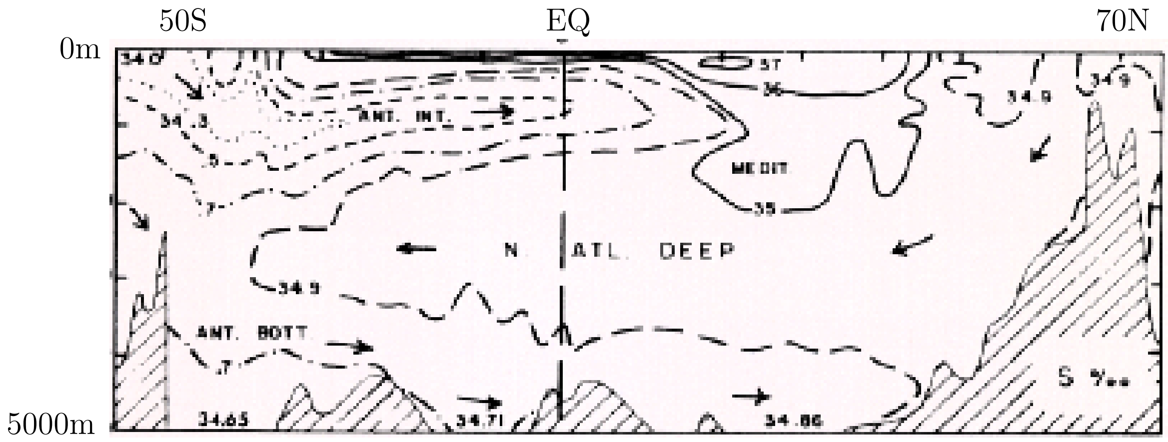
- Water mass formation.
- Is the thermohaline circulation driven really driven by thermal and freshwater forcing?
- Deep Western Boundary Currents.
- Multiple equilibria and abrupt change.

WATER MASSES AND THEIR FORMATION

There are three dominant abyssal water masses:

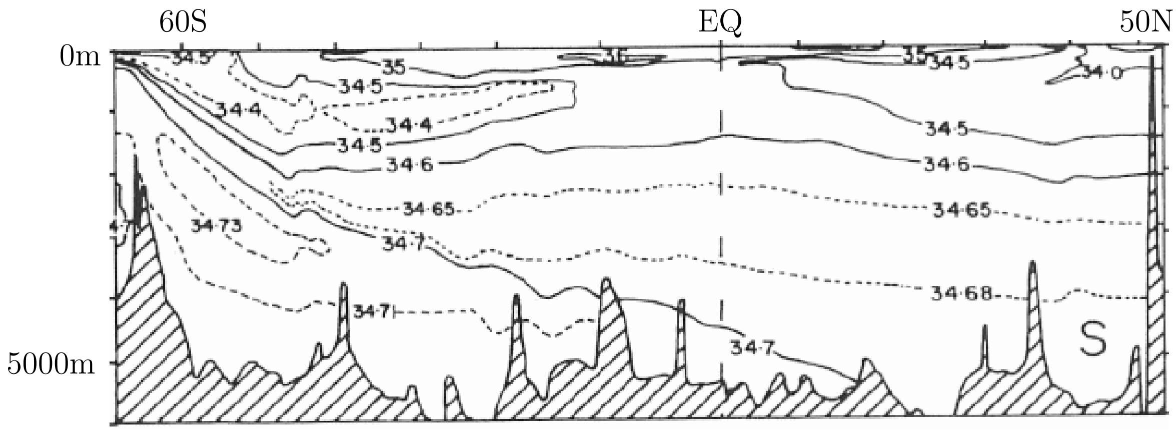
- Antarctic Intermediate Water (AAIW);
- North Atlantic Deep Water (NADW);
- Antarctic Bottom Water (AABW).

Atlantic salinity section (Pickard and Emery 1990):



However *no deep water is formed in the North Pacific.*

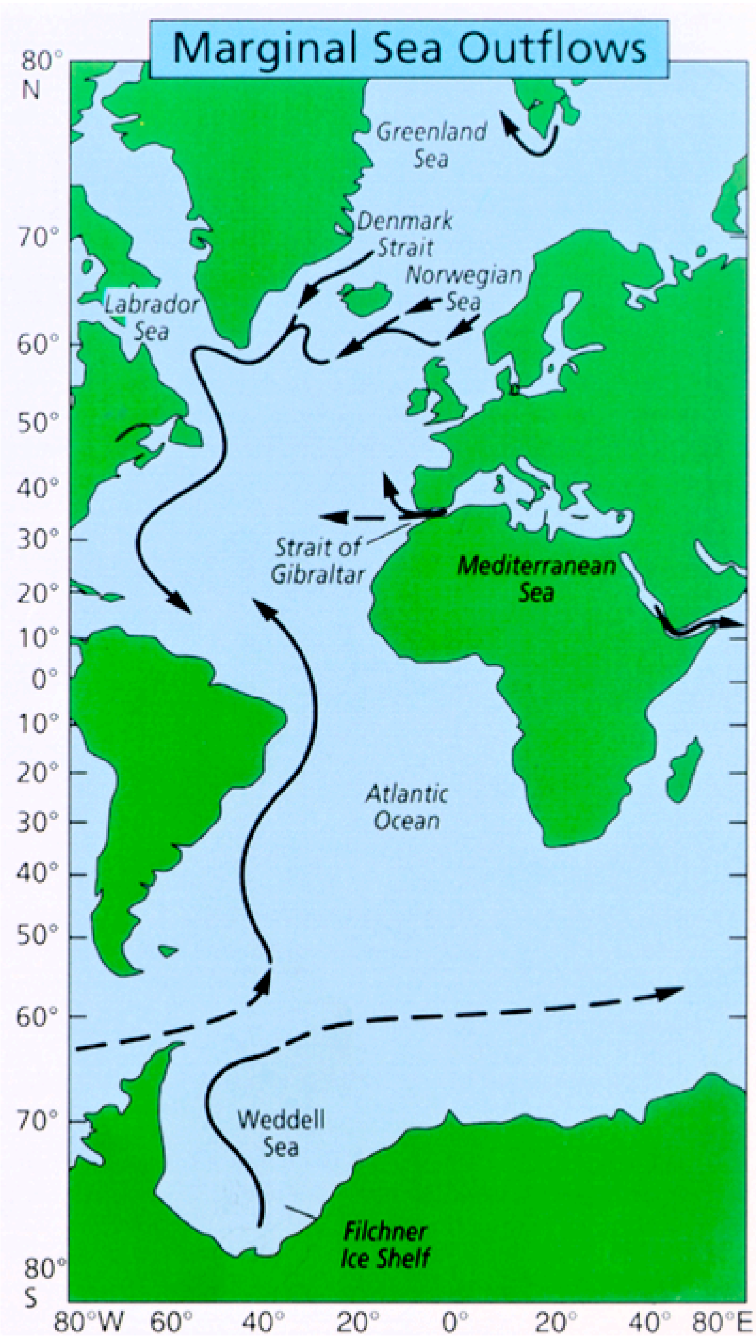
Pacific salinity section:



This leads to the asymmetry in heat transports between the Atlantic and the Pacific (page 1-4).

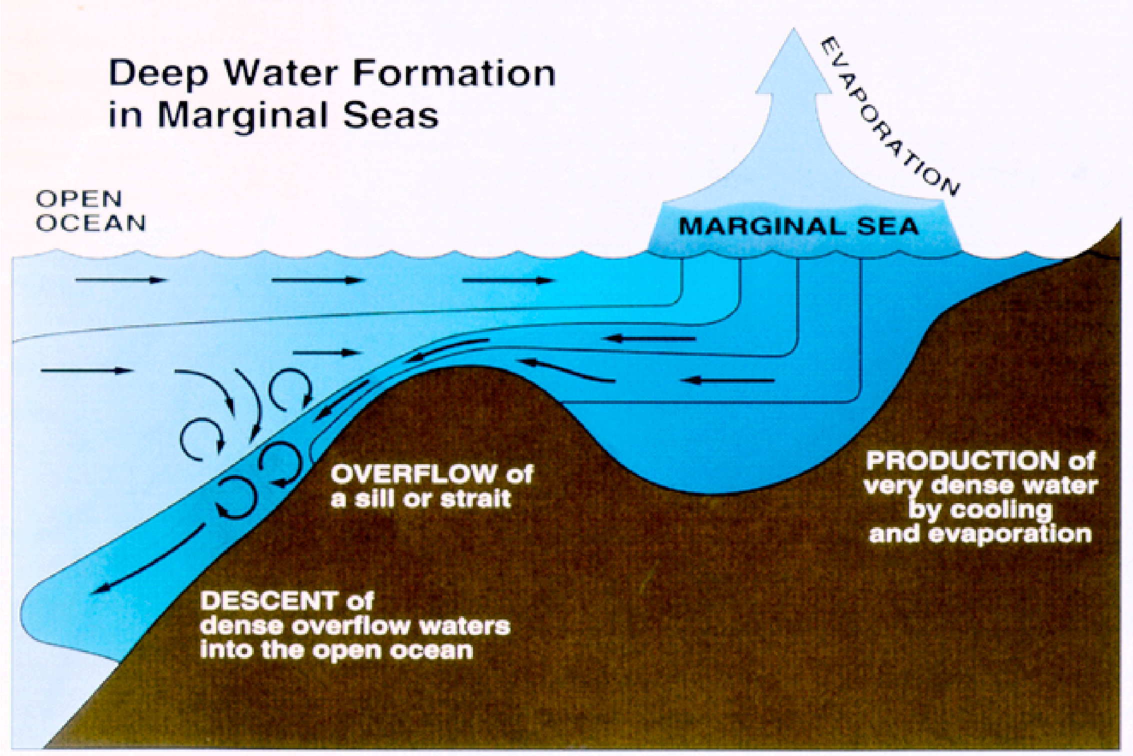
The densest water masses are formed in semi-enclosed or marginal seas, where a small volume of water is trapped for an extended period and exposed to intense buoyancy loss $\Rightarrow$ large changes in density can be achieved.

These marginal sea waters then *overflow* into the open abyssal ocean:



(Price, 1994)

The densities of the water masses change dramatically due to mixing and entrainment in the overflows (Price 1994):



	source		**product**	
densest ↓	Filchner Ice Shelf		AABW	↑ densest
	Greenland Sea	→	NADW	
	Norwegian Sea		NADW	
	Mediterranean		MIW	

ROLE OF MECHANICAL FORCING

The ocean is heated and cooled at its surface. This is an inefficient way of driving a circulation — try boiling a pot of water under the grill!

To maintain a circulation and stratification over the entire depth of the oceans requires mechanical forcing $\Rightarrow$ the thermohaline circulation is, in fact, mechanically driven.

Suppose we have $S \sim 20\,\mathrm{Sv}$ of NADW production.

This must be balanced by upwelling of magnitude $w^* \sim S/A$, where A is the surface area of the oceans.

Taking $A \approx 3 \times 10^{14}\,\mathrm{m}^2$ gives $w^* \sim 0.7 \times 10^{-7}\,\mathrm{m\,s}^{-1}$.

Now, following Munk (1966), assume that the upwelling of cold abyssal water is balanced by mechanical mixing of heat down from the surface by breaking internal waves:

$$w^* \frac{\partial \theta}{\partial z} \approx \frac{\partial}{\partial z}\left(\kappa_v \frac{\partial \theta}{\partial z}\right).$$

This gives the required diapycnal mixing rate:

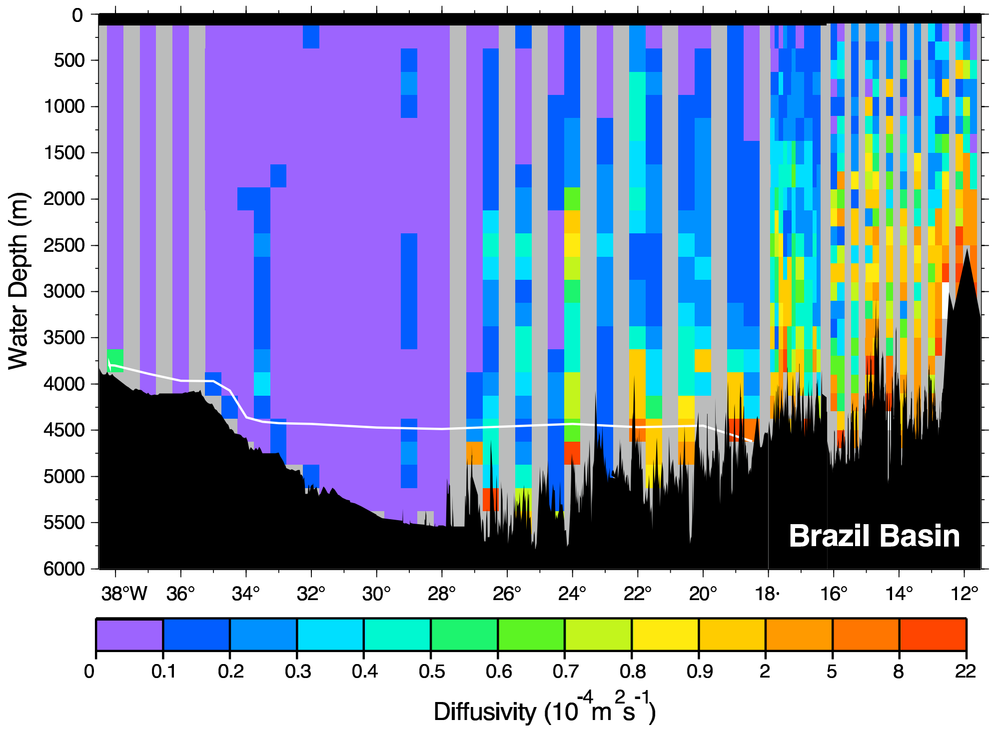
$$\kappa_v \sim w^* H \sim 10^{-4}\mathrm{m}^2\mathrm{s}^{-1}.$$

However tracer release experiments and microstructure measurements suggest $\kappa_v \sim 10^{-5}\mathrm{m}^2\mathrm{s}^{-1}$!

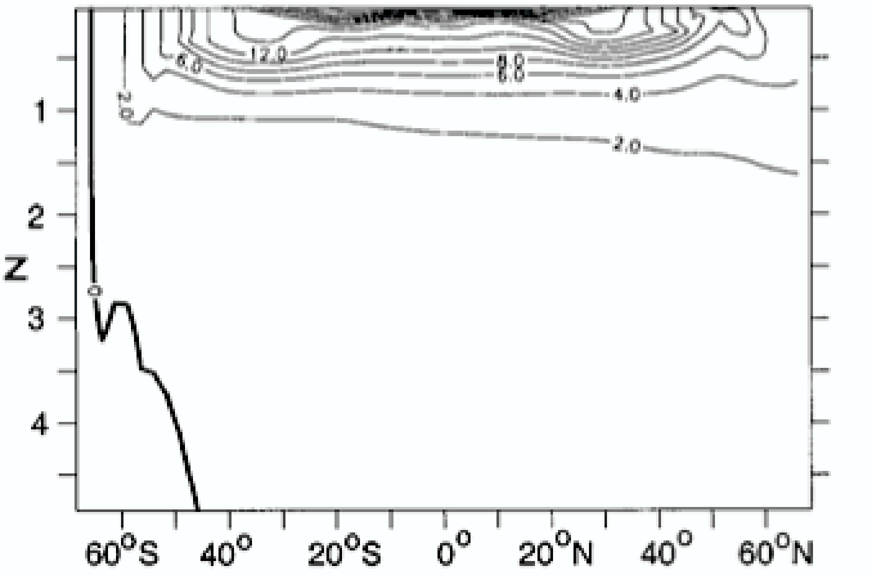
There are two leading candidates to resolve this paradox:

- Enhanced mixing over rough topography

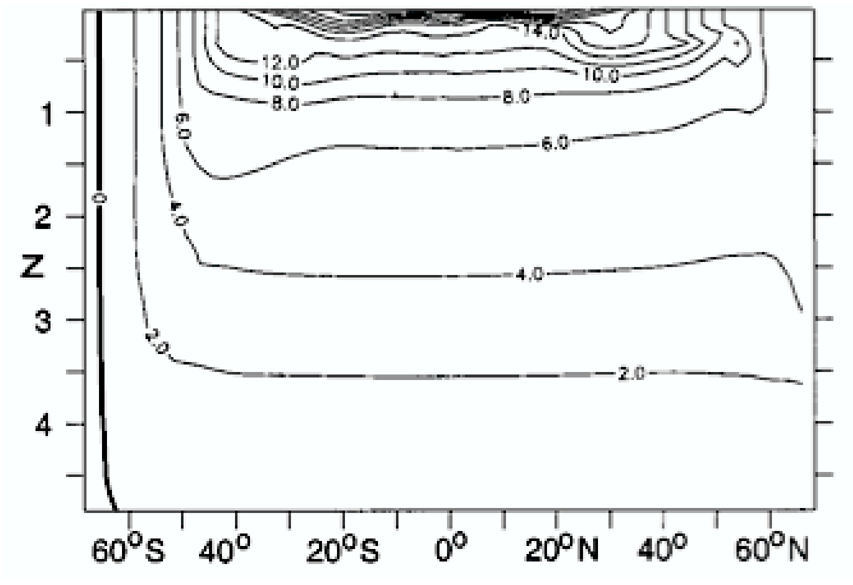
(data from Polzin et al. 1997)



- Wind-driven adiabatic upwelling in the ACC:



Zonally-averaged potential temperature from a numerical integration without a Drake Passage — there is no ACC, and the stratification and overturning circulation are confined to the surface.



The same with a Drake Passage and ACC — an abyssal stratification and overturning circulation is obtained (Vallis 2000).

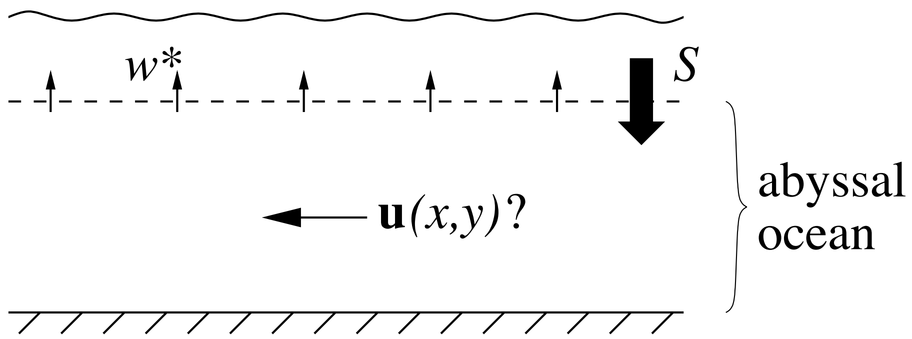
DEEP WESTERN BOUNDARY CURRENTS

Why is the abyssal circulation intensified at the western margin of basins?

... addressed in a famous series of papers by Stommel and Arons (1958-1960).

Assumptions:

- abyssal ocean represented by a layer of uniform thickness;
- no variations in bottom topography;
- localised sources of deep water at high latitudes, balanced by slow upwelling, w^*, over the remainder of the ocean.



a. Interior circulation

Away from boundaries, circulation will be geostrophic:

$$u = -\frac{1}{\rho_0 f}\frac{\partial p}{\partial y}, \quad v = \frac{1}{\rho_0 f}\frac{\partial p}{\partial x}. \tag{4.1}$$

Substituting above into continuity equation,

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0, \tag{4.2}$$

gives large-scale vorticity balance:

$$\beta v = f\frac{\partial w}{\partial z}. \tag{4.3}$$

Integrating from sea floor (where $w = 0$) to the top of the abyssal layer (where $w = w^*$) gives:

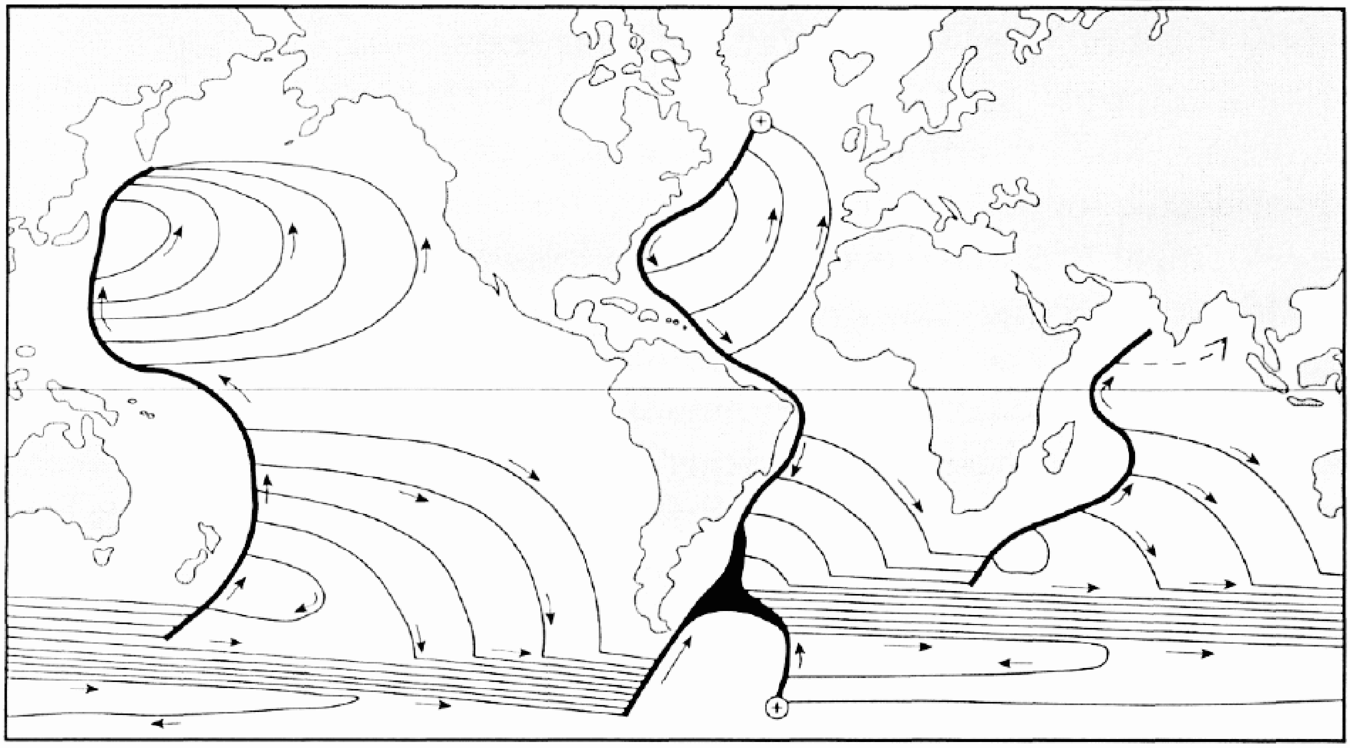
$$\beta \int v\, dz = f w^*. \tag{4.4}$$

$\Rightarrow$ poleward, i.e., towards the sources of deep water!

b. The Deep Western Boundary Current

The deep flow cannot be poleward everywhere, e.g., we know there is a net equatorward flow of NADW in the North Atlantic.

To resolve this paradox, Stommel predicted the existence of *deep western boundary currents.* (Can solve for these mathematically by adding linear friction to the momentum balance.)



The prediction of the Deep Western Boundary Current in the North Atlantic is perhaps the only example of major ocean current having been predicted using a theoretical model before it was actually observed.

To confirm the theoretical prediction, Swallow and Worthington (1961) dropped neutrally-buoyant floats into the predicted DWBC and indeed observed them move rapidly southward. However, with hindsight, there is a high probability the floats could have moved the other way! (due to the eddy field)

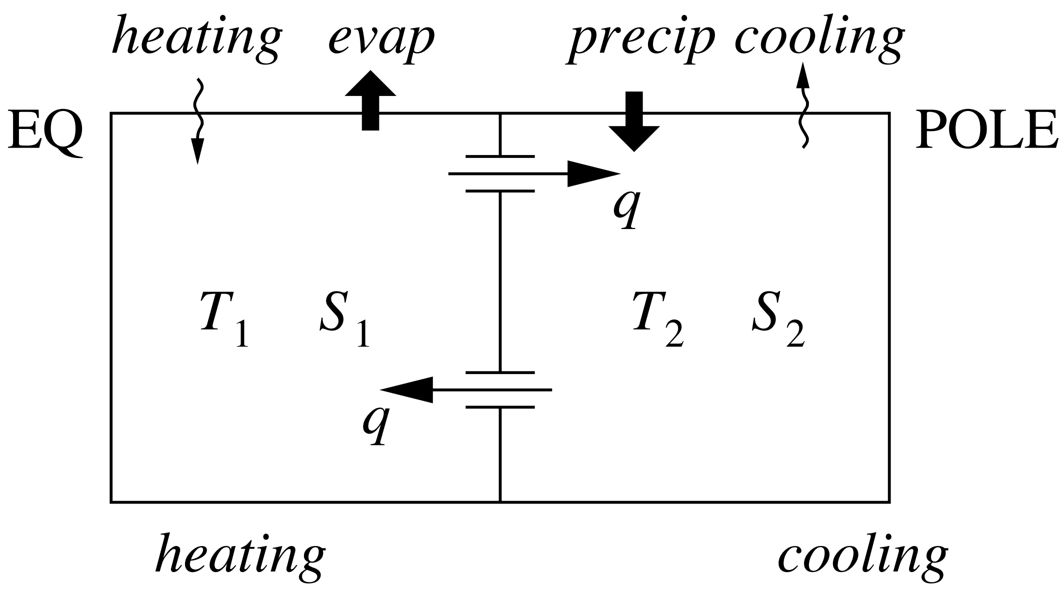
Nevertheless, the existence of a DWBC is now clearly established, e.g., from tracer observations (see page 1-18).

MULTIPLE EQUILIBRIA AND ABRUPT CHANGE

Can the thermohaline circulation possess more than one stable mode of operation? Can deep water be formed in the Pacific rather than the Atlantic?

First addressed in a remarkable paper by Stommel (1961).

Two-box model of a hemispheric basin:



Within each box, T and S are assumed well mixed.

A circulation, strength q, flows through two pipes connecting the boxes. Assuming this acts essentially as non-rotating density current, we let

$$q = k(\alpha\,\Delta T - \beta\,\Delta S). \tag{4.5}$$

What are the simplest, physically motivated boundary conditions for T and S?

- Air-sea heat exchange tends to restore the ocean temperature to equilibrium values over relatively short time-scales.
- However the evaporation and precipitation rates do not depend on the salinity of the ocean.

Therefore want *restoring* boundary conditions on T and *fixed flux* boundary conditions on S.

We can simplify further if we fix the temperatures ($\Rightarrow$ infinitely fast restoring).

A salt budget for either box gives:

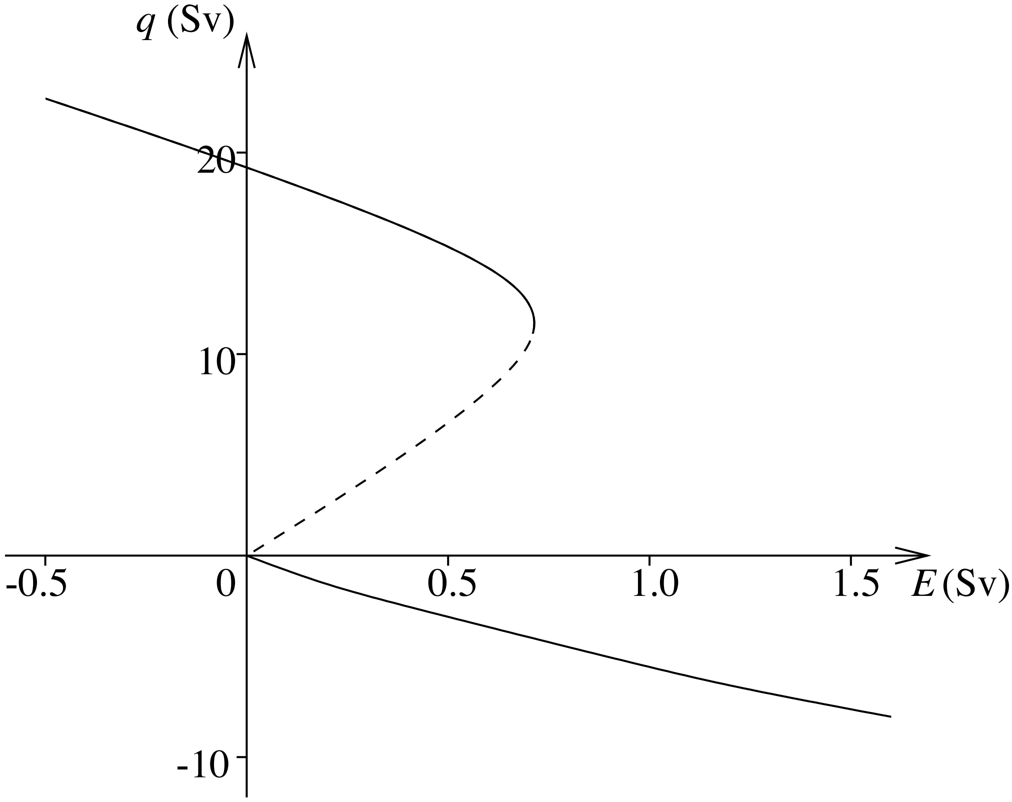
$$\begin{aligned} |q|\, S_1 &= (|q| + E) S_2 \\ \Rightarrow |q|\, \Delta S &\approx E S_0. \end{aligned} \tag{4.6}$$

(The modulus sign is present because the result is independent of flow direction.)

Eliminating ΔS between (4.5) and (4.6) gives

$$|q|q - k\alpha\, \Delta T\, |q| + k\beta E S_0 \approx 0. \tag{4.7}$$

Equilibrium solutions for typical model parameters:



Solid lines represent stable equilibria and the dashed line unstable equilibria.

For the present-day North Atlantic ($E \sim 0.5\,\mathrm{Sv}$) there are two stable equilibria:

- a *fast* or *thermally-direct* equilibrium, with sinking at high latitudes ($q \sim 15\,\mathrm{Sv}$).
- a *slow* or *thermally-indirect* equilibrium, with sinking at low latitudes ($q \sim -2\,\mathrm{Sv}$).

These two equilibria arise due to the opposing nature and different time-scales of the freshwater and thermal forcing.

Global warming scenario:

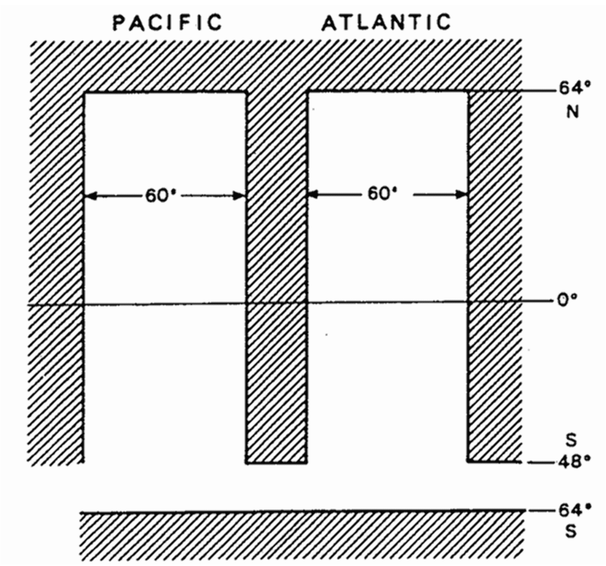
increased atmospheric $CO_2 \Rightarrow$ warmer air
$\Rightarrow$ increased moisture capacity $\Rightarrow$ larger E

According to the graph, as E increases the thermohaline circulation will initially weaken.

However once E exceeds $0.7\,\mathrm{Sv}$, the high-latitude sinking equilibrium no longer exists, and the circulation will collapse into the low-latitude sinking state.

Note that if atmospheric levels of CO_2 were to subsequently decrease, the circulation would remain in the low-latitude sinking state.

Marotzke and Willebrand (1991) looked for multiple equilibria in an idealised OGCM (4° resolution):



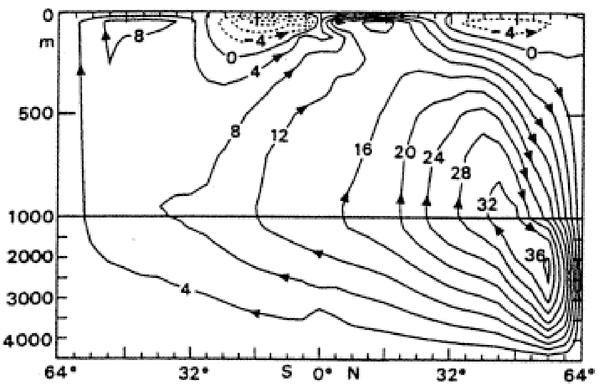
4 hemispheric basins

$\Rightarrow 2 \times 2 \times 2 \times 2 = 16$

potential equilibria

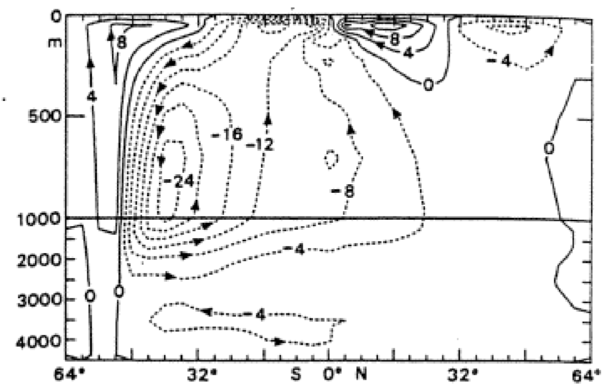
They found 4 (panels show meridional overturning, Sv):

a. northern sinking



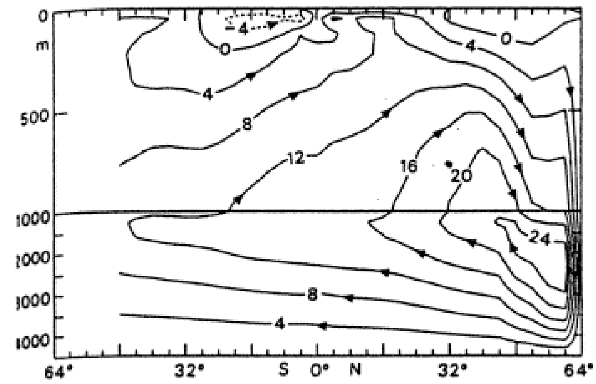
Atlantic + Pacific

b. southern sinking

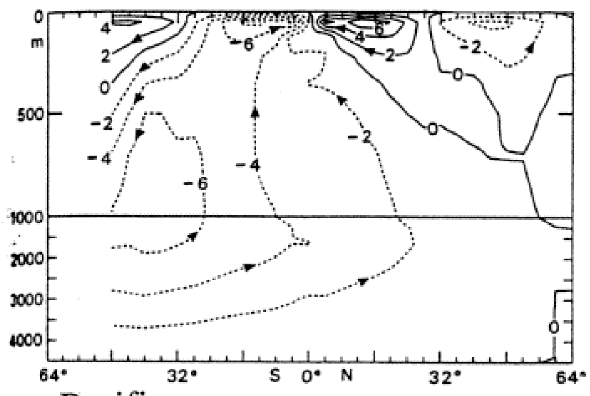


Atlantic + Pacific

c. conveyorbelt

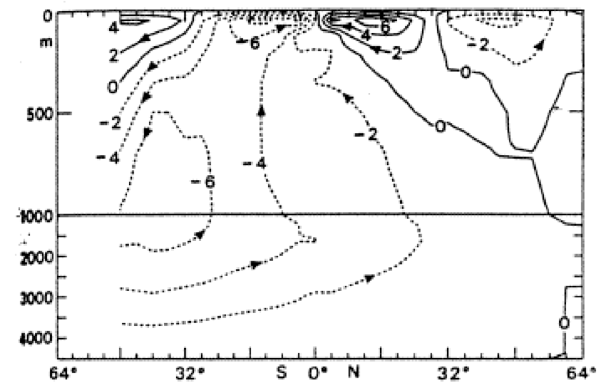


Atlantic

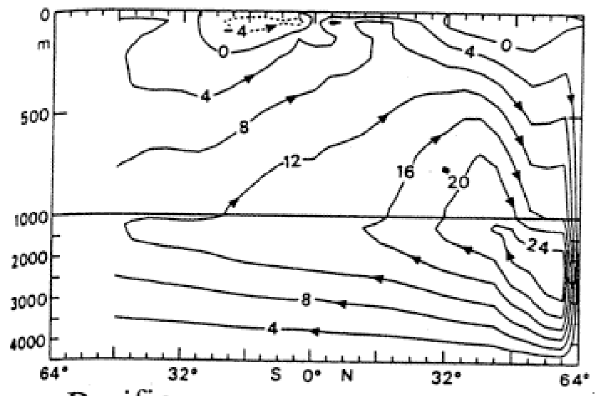


Pacific

d. inverse conveyorbelt



Atlantic



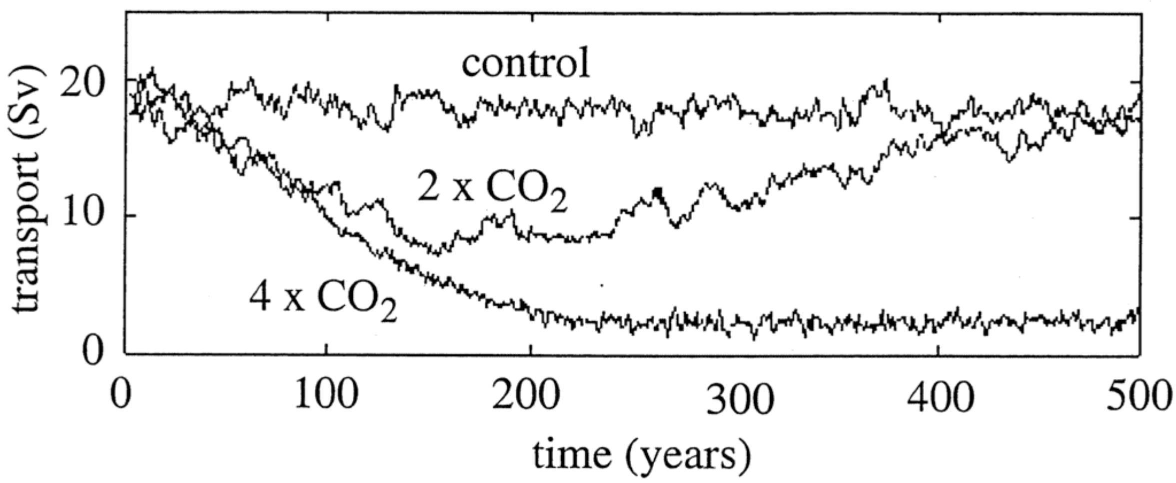
Pacific

Manabe and Stouffer (1994) studied the effect of increasing atmospheric CO_2 levels on the North Atlantic thermohaline circulation in a coupled ocean-atmosphere GCM (4° resolution).

They performed three experiments in which:

- atmospheric CO_2 is held at its pre-industrial level;
- atmospheric CO_2 increases to 2 times its pre-industrial level;
- atmospheric CO_2 increases to 4 times its pre-industrial level.

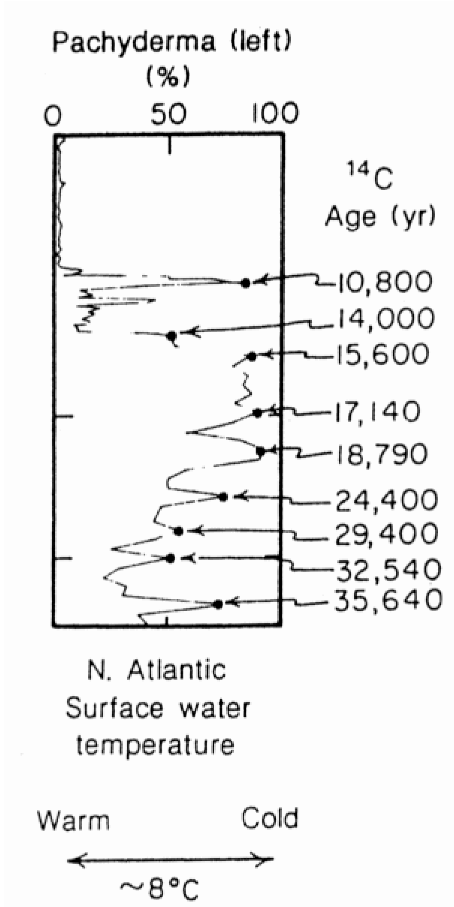
Maximum North Atlantic overturning in the 3 experiments:



There is also evidence from ice-cores and sediment records that North Atlantic climate has changed abruptly in the past, consistent with (but not proof of) abrupt change in the thermohaline circulation.

Example of a sediment record showing the abundance of pachyderma shells, a proxy for surface water temperature (west of the UK):

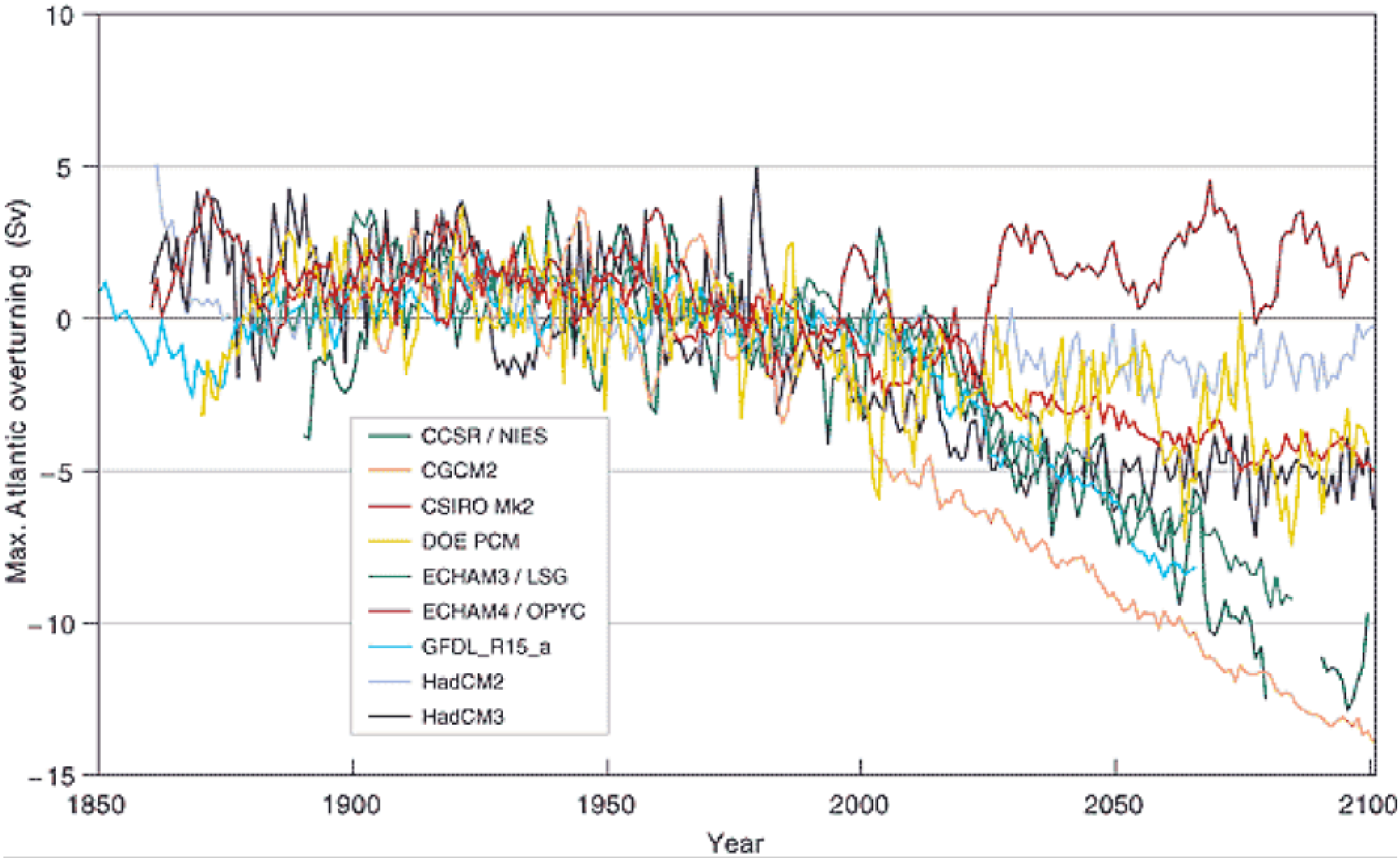
(Broecker 1987)



Abrupt warming occurred $\sim 15\,000$ *years ago at the end of the last glacial maximum.*
However cold temperatures abruptly returned $\sim 10\,800$ *years ago during the "Younger-Dryas" event, possibly due to a massive injection of freshwater from the collapsing ice sheets shutting down the THC?*

THE FUTURE?

Predictions of several state-of-the-art climate models for the *change* in North Atlantic overturning over the next century:

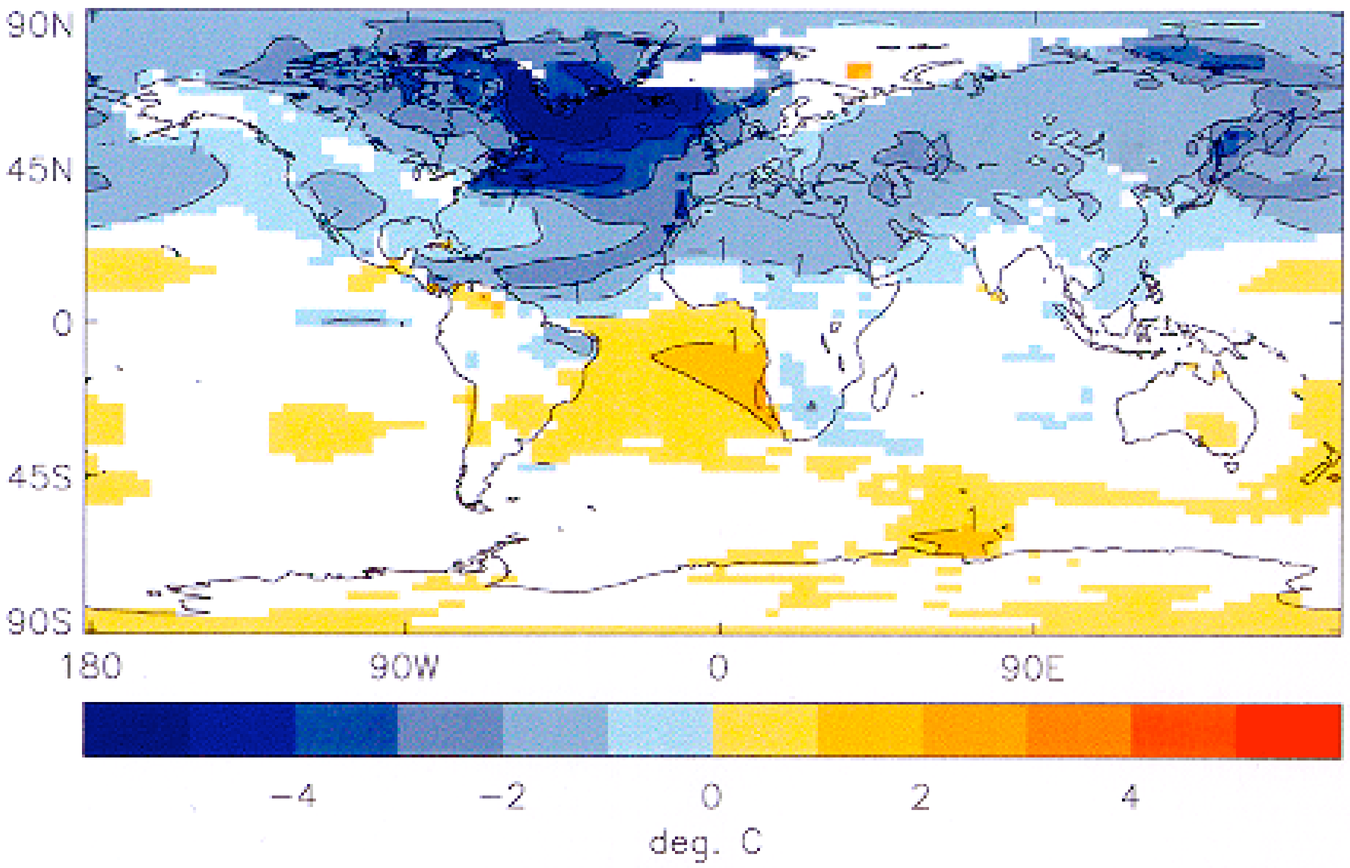


(IPCC 2001)

Note there are wide discrepancies!

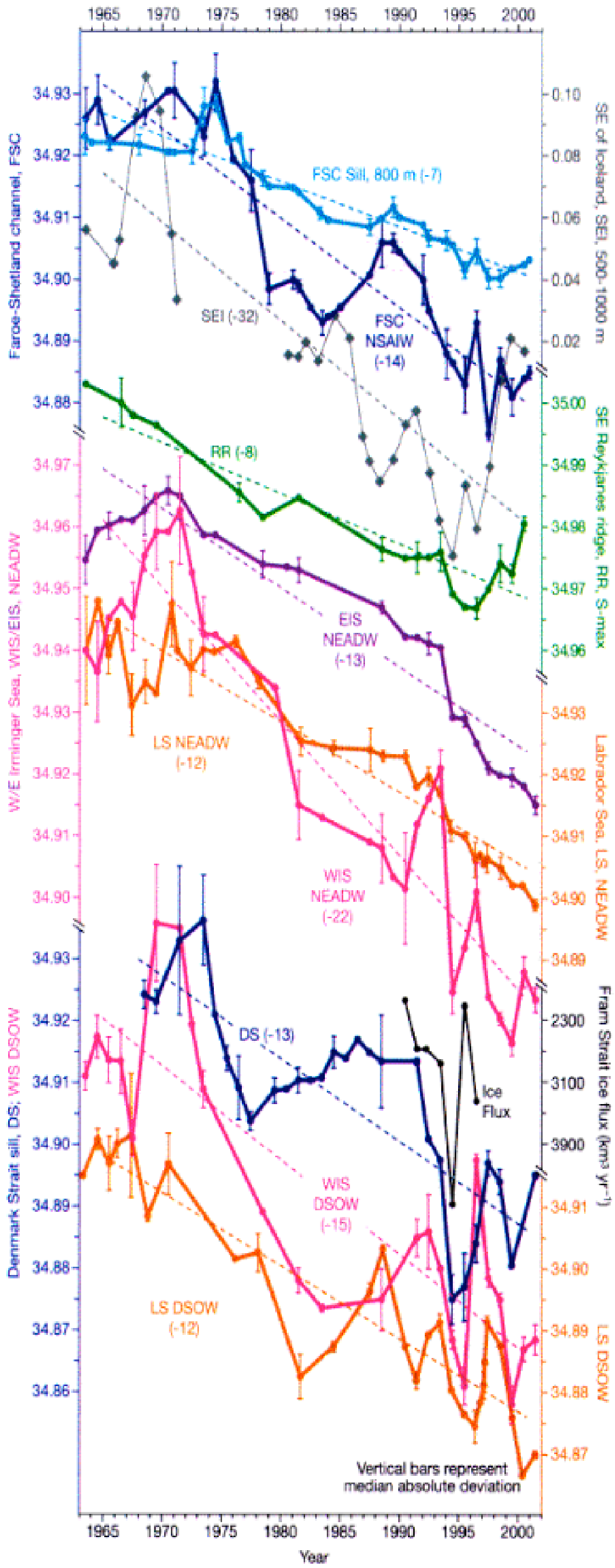
Even the highest resolution models ($\sim 1^\circ$) are unable to properly resolve the water mass formation processes, the overflows, and even the boundary currents
$\Rightarrow$ one should be cautious in interpreting their predictions!

The impact of a forced thermohaline circulation shutdown in the Hadley Centre coupled ocean-atmosphere model:



(Vellinga and Wood 2002)

There *is* substantial observational evidence of freshening of the high latitude North Atlantic, both at the surface and in the NADW layer (Dickson et al. 2002):



However we do *not* know, with confidence, whether the North Atlantic overturning circulation is also changing (despite the recent claims of Bryden et al. 2005).

SUMMARY OF MAIN POINTS:

- Deep water is formed in the Atlantic, but not in the Pacific.
- The densest water masses are formed in marginal and semi-enclosed seas. The water mass properties are modified substantially in the dense water overflows.
- The abyssal circulation is concentrated in Deep Western Boundary Currents.
- The thermohaline circulation may possess more than one stable mode of operation. Increased high-latitude precipitation in a warmer climate may lead to a reduction, or shutdown, in the North Atlantic thermohaline circulation.
- *However* the thermohaline circulation is sensitive to a number of processes that are currently poorly represented in ocean general circulation models. Thus the results of such models should be regarded as tentative in nature.

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